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Deep Sky Objects and the X-ray Background

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Abstract. Deep observations of the X-ray Sky have now resolved most of the X-ray Background. Obscured active galaxies are a key component. The obscured objects which dominate at fluxes above $10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ are discussed and models in which the growth of wind-blowing active nuclei determine both black hole and galaxy mass are presented. The power from accretion is large and can easily influence the gas in a host galaxy, as well as heat the intergalactic medium.

1. Introduction

Observations with Chandra and XMM are revolutionizing our understanding of the X-ray Background (XRB). Chandra has at last resolved the 2–7 keV part of the hard XRB (Mushotzky et al 2000; Garmire et al 2000; Giacconi et al 2000). Since the 2–7 keV spectrum of the Background attaches smoothly onto the rest of the spectrum up to its νF_ν peak at about 30 keV, we may fairly say that the X-ray Background is now beginning to be understood. The soft X-ray Background was of course resolved by ROSAT (Hasinger et al 1998), but the spectrum below 1 keV is much steeper than that of the harder background and dominated by different components.

In the 2–7 keV band the sources at flux levels of $\sim 10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ appear to be roughly one third normal quasars, one third galaxies and the remaining third are optically faint (Mushotzky et al 2000; Barger et al 2000). It is plausible that all are powered by active galactic nuclei (AGN), since the luminosities are all much greater than for the distributed binaries etc in galaxies and starbursts (such sources do however appear at lower flux levels). The nucleus itself must be obscured in the second two classes of object. Obscured AGN have been a major component of most models for the XRB since first proposed by Setti & Woltjer in 1989. The reason is the spectrum of the XRB which is flatter than any known class of extragalactic X-ray source (see Boldt 1987; Fabian & Barcons 1992). A range of absorption and redshift in the sources can result in the observed spectrum (Madau et al 1994; Matt & Fabian 1994; Comastri et al 1995; Wilman & Fabian 1999).

In this talk I shall concentrate on the absorbed sources. First I briefly review nearby obscured AGN, then summarise Chandra results which show that the optically faint sources are likely obscured quasars. Next I show that most accretion power is in distant obscured AGN and that the obscuring medium must cover most of the Sky subtended at such nuclei. Finally I show that a model for galaxy formation in which a significant fraction of the central matter

in a galaxy remains in the form of X-ray absorbing gas which is eventually blown away by a wind from the central quasar when it is powerful enough, can explain the development of both black holes in galaxy bulges and the XRB.

2. Obscured AGN

2.1. Seyfert II galaxies

Obscured AGN, in which the power source lies behind a significant column density of gas which is local to the nucleus, are common and generally known as Seyfert II galaxies. Strictly speaking, the name refers to the optical appearance of the object (ie absence of broad lines and presence of narrow lines characteristic of photoionized gas) but I shall use Type II to denote any object where the nucleus is absorbed (i.e. even so absorbed that no narrow lines from photoionized gas are detectable). The column densities range from below 10^{22} to above $10^{25}\,\mathrm{cm}^{-2}$. The PDS instrument on BeppoSAX has played an important role here in probing the higher column density regime (e.g. Maiolino et al 1998). There appear to be at least as many Compton-thick Seyfert IIs ($N_{\mathrm{H}} > 1.5 \times 10^{24}\,\mathrm{cm}^{-2}$) as Compton thin ones ($N_{\mathrm{H}} < 1.5 \times 10^{24}\,\mathrm{cm}^{-2}$).

Just how common Seyfert II galaxies are is uncertain. Optical-based estimates suggest about 3 times that of Seyfert I galaxies, but they are often insensitive to the Compton-thick ones with high covering fraction. Unfortunately there is as yet no survey of the hard X-ray sky which can sort this out in a definitive way. This is a task for EXIST (Grindlay 2000). For now we can make use of rough arguments such as that of Matt et al (2000). We note there that the 3 nearest AGN with luminosities above $10^{40}\,\mathrm{erg\,s}^{-1}$ – NGC4945, the Circinus galaxy and Cen A – all lie within 4 Mpc and have absorbed nuclei. The column density for Cen A $\sim 10^{23}\,\mathrm{cm}^{-2}$ and those for NGC4945 and Circinus are 2 and $4 \times 10^{24}\,\mathrm{cm}^{-2}$ respectively. Two of the three are therefore Compton thick. NGC4945 only appears to host an AGN at hard X-ray wavelengths. The X-ray luminosity function for unabsorbed AGN (Miyaji et al 1998) predicts that there is only a 5 per cent chance of detecting an object within a radius 4 Mpc. The probability of 3 or more is 2×10^{-5}! Only if obscured AGN outnumber unobscured ones by about a factor of 10 to one does the probability exceed two percent. Even though we are using only 3 objects it is highly likely that Type II objects are common, and present in about 10 per cent of all L^* galaxies. At least one half of all local ultraluminous IRAS galaxies (ULIRGs) are then obscured AGN.

2.2. Obscured quasars – Type II quasars?

If most local AGN hide behind large columns of absorbing material, is it also true for more distant and powerful ones, like the quasars? Although it might at first thought seem obvious that the answer has been known for ages, it is not. There is no clear optically-identified population resembling a more powerful version of the Seyfert II galaxies. A few objects began to emerge from ASCA and BeppoSAX hard imaging, but whether they have quasar luminosity is debatable (Halpern et al 1999). I suspect that such luminous objects are either unabsorbed or highly

absorbed ($N_{\rm H} \gg 10^{22}\,{\rm cm^{-2}}$). Perhaps the radiation pressure and winds from quasars are powerful enough to blow away intermediate column density material.

The situation is now changing with Chandra data, which routinely shows a few powerful obscured AGN per image. A simple example is the brightest serendipitous source in the field of the lensing cluster A2390. This hard X-ray source has a photometric redshift of about one, an intrinsic $N_{\rm H} \sim 10^{23}\,{\rm cm^{-2}}$ and a 2-10 keV luminosity (unabsorbed) of $3 \times 10^{44}\,{\rm erg\,s^{-1}}$ making it a Type II quasar. The optical/near infrared appearance and colours show no sign of the active nucleus. Such sources are common (Crawford et al 2000; Barger et al 2000).

It is only in the mid infrared that the central power of the object in the A2390 field (Fabian et al 2000) is revealed since it is detected by ISO (Lemonon et al 1998). The emission at 7.5 and 15 microns is far above that expected from the starlight of the host galaxy and is consistent with that absorbed from the X-ray emitting nucleus (Wilman et al 2000). The MIR colours indicate that the reradiating dust is warm to hot (200 – 1500 K) so probably close to the nucleus. It should peak its emission at about 60 microns. The infrared connection is important in showing that we are dealing with absorption of a quasar in the X-ray band and not some new class of source with a 'funny' spectrum.

It is also plausible that Type II quasars outnumber normal Type I quasars. Only then can the spectrum and source counts of the hard XRB be accounted for. Simple correction of the spectrum of the XRB for absorption leading to the intrinsic energy density of radiation due to accretion (Fabian & Iwasawa 1999) agrees with the local mean density of massive black holes (Magorrian et al 1998; Merritt & Ferrarese 2000), if the accretion efficiency is the 10 per cent typical of radiatively efficient accretion discs. This implies that about 85 per cent of accretion power has been absorbed (Fabian & Iwasawa 1999). In turn this means that the absorbing material covers most of the sky, as seen by the accreting black holes. To build a massive black hole by efficient accretion by redshift 2 requires that a quasar-like luminosity is emitted (Fabian 1999). In conclusion, obscured quasars must be common.

3. The central black hole and galaxy formation

The observed correlation between black hole mass and the stellar mass of the host bulge (Magorrian et al 1998), and more recently with the velocity dispersion of that bulge (Gebhardt et al 2000; Ferrarese & Merritt 2000), implies some link between the growth of a massive black hole and the growth of its host galaxy (or at least the bulge of that galaxy). If the XRB is revealing the growth of massive black holes, albeit obscured ones, then it should also convey information on the growth of bulges. Quite how to decipher that information is not yet clear.

One possibility is that the bulge and black hole grow from gas together, with the process terminated when a wind from the quasar becomes powerful enough (Silk & Rees 1998; Fabian 1999). Consider an isothermal bulge of velocity dispersion v in which a significant fraction f of the cooled gas remains in the form of cold dusty clouds, instead of forming stars. Let the central black hole grow by accretion and blow a wind of velocity $v_{\rm w}$ with power fraction a of the Eddington limit, i.e. $L_{\rm w} = aL_{\rm Edd}$. Analogous to the Eddington limit for point

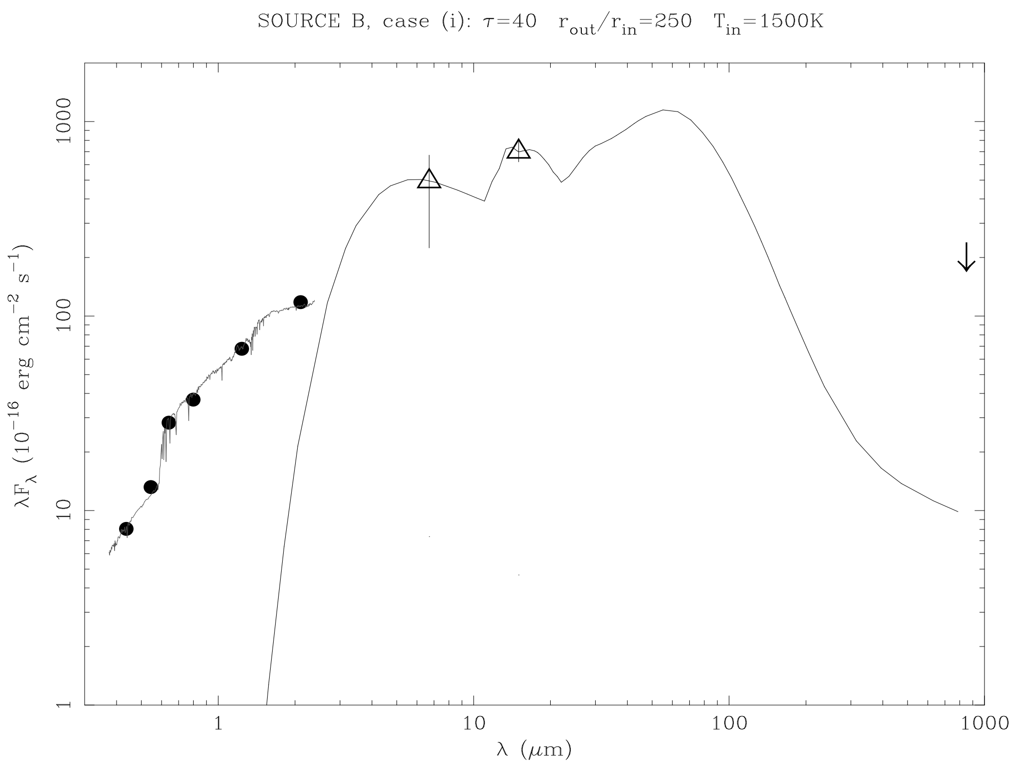

Figure 1. Spectral Energy Distribution of lensed X-ray source in the field of A2390 (Fabian et al 2000). Optical and near-infrared fluxes indicate an early-type host, ISO mid-infrared points are fitted by a hot dust model. see Wilman et al 2000. Since this talk was presented, Cowie et al (2001) have shown that the redshift is significantly greater than that assumed here ($z \sim 1$).

masses, a wind can eject matter from a distributed mass if the force is large enough (Fabian 1999; Silk & Rees 1998 use an energy argument). A column density of gas is ejected if

$$L_{\rm w} > v^4 v_{\rm w} f/G.$$

This happens when the mass of the hole

$$M_{\rm h} \approx \frac{v^4 \sigma_{\rm T}}{4\pi G^2 m_p} \frac{v_{\rm w}}{c} \frac{f}{a},$$

which agrees well with the Gebhardt et al (2000) relation if $\frac{v_{\rm w}}{c}\frac{f}{a} \sim 1$ and the expulsion of the gas also stops the growth of the bulge, as well as the hole. At the point of expulsion the column density of cold gas $N \sim \sigma_{\rm T}^{-1}$, so the growth of the hole is Compton thick.

The expulsion phase can be identified with broad absorption line quasars, BALQSO, suggesting that $v_{\rm w} \sim 30,000\,{\rm km\,s^{-1}}$. A normal, unobscured quasar is only seen after gas expulsion and is presumably due to the draining of the remaining centrifugally-supported gas close to the hole.

As mentioned in the Introduction, there have been many detailed attempts to explain the XRB in terms of AGN with various amounts of absorption over a range of redshifts. Usually the observed present-day distribution has been extrapolated backwards in time. Richard Wilman, Paul Nulsen and I (2000) have tried to build a model based on a simple semi-analytic model for galaxy formation where we work forward in time from a redshift of about ten. All dark matter haloes initially contain a seed black hole of mass $M_{\rm seed}$. To make stars the gas component in the haloes has to cool. Initially the cooling time is less than the free-fall time throughout the halo producing what we term a dwarf galaxy (supernova feedback prevents all gas cooling into stars). Such dwarfs merge until what we term a normal galaxy is built. This is a galaxy within which the cooling time of its gas exceeds the free-fall time, so that a hot halo occurs. The central black hole, which is now many tens of $M_{\rm seed}$ then accretes from that hot gas (which also progressively cools to make stars) via Bondi accretion. We assume that the radiative efficiency of accretion is always 10 per cent and the 2–10 keV luminosity is 3 per cent of the total. Accretion is terminated by i) exhaustion of the hot gas supply, ii) a new collapse or iii) the wind from the central quasar exceeding the above force balance. The last possibility dominates in practice.

If the star formation is inefficient so that $f \sim 0.37$, $M_{\rm seed} \sim 1.6 \times 10^6\,{\rm M}_\odot$ and there is a final unobscured phase lasting 9×10^7 yr we find that we can account for the spectrum of the XRB, the X-ray luminosity function of quasars and also the X-ray source counts fairly well (Wilman et al 2000). The model does however give a spectral excess below 3 keV. This can be fixed by assuming that gas expulsion is anisotropic, leaving behind a torus of gas (say that which is centrifugally supported). Otherwise we only have Compton thick and unobscured objects. We also fail to have many massive black holes. This is mainly because we do not treat mergers of normal galaxies and galaxies in groups and clusters.

The reasonable success of this model does not of course prove that it is correct, but it does show that models can be built. We used accretion of hot gas since it must occur and is relatively easy to model. It also overcomes the angular

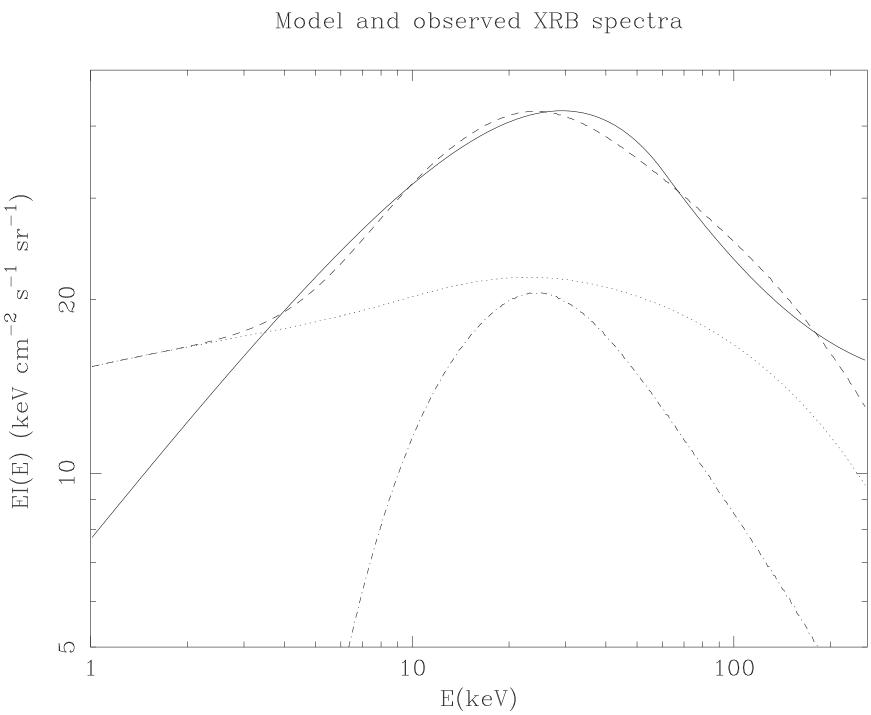

Figure 2. XRB spectrum from the model of Wilman et al (2000b). The solid line indicates the observed spectrum and the dashed line the model due to the sum of unobscured quasars (dotted line) and Compton-thick objects (lower dashed line). A modification for centrifugally-supported gas not ejected by the wind allows the discrepancy below 3 keV to be eliminated. Note that Chandra has little sensitivity above 7 keV so should not readily probe the Compton-thick population in the model (however the model fails to deal with luminous objects in groups and clusters which may be detected by Chandra if at high enough redshifts). XMM has better sensitivity up to 10 keV may pick up the tip of this population.

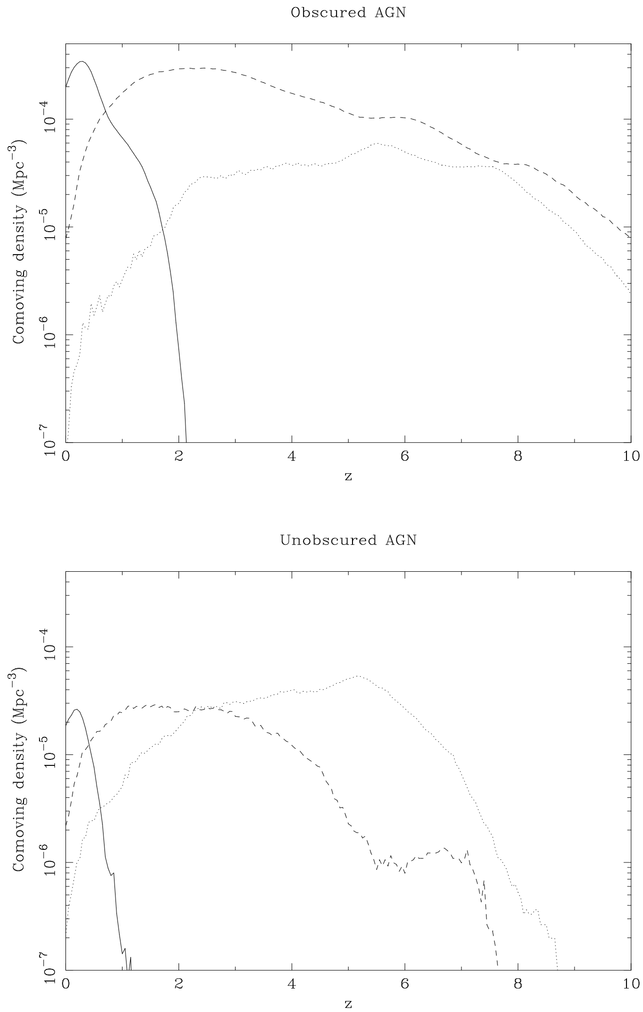

Figure 3. The redshift dependence of the X-ray luminosity functions of the obscured and unobscured populations in the model of Wilman et al (2000b). Solid lines are objects with intrinsic 2–10 keV luminosities below $L = 10^{43}\,\mathrm{erg\,s^{-1}}$, dashed lines those with $10^{43} < L < 10^{44}\,\mathrm{erg\,s^{-1}}$, and dotted lines those with $L > 10^{44}\,\mathrm{erg\,s^{-1}}$. Note that the model predicts many reasonably luminous objects above z of 5, although most are obscured.

momentum problems in the accretion of cold gas. Other models involving more realistic merger histories and accretion of cold gas need to be tried. In our model the black hole plays an important part in the evolution of the galaxy in that it expels the gas which both fuels the quasar and from which stars form, thereby ending further star formation.

4. The power of accretion

The total power radiated by (obscured) AGN may be 10–50 per cent of that radiated by stars. If accompanied by winds (as seen in BALQSO) considerable mechanical energy may result, which is presumably thermalized in the host galaxy and the intergalactic and intra-group and -cluster media. Indeed it may be important for shifting the cluster X-ray luminosity–temperature relation from the gravitational collapse $L_{\rm x} \propto T^2$ scaling to the observed T^3 one (Wu et al 2000). For ten per cent accretion efficiency, a mean black hole density of $\rho_{\rm BH} = 6 \times 10^5\,{\rm M}_\odot\,{\rm Mpc}^{-3}$ corresponds to $6 \times 10^{58}\,{\rm erg\,Mpc}^{-3}$ or $3.7\,{\rm keV}$ particle^{-1} if $\Omega_{\rm baryon} = 0.08, h = 0.5$.

The gravitational binding energy of a galactic bulge, where the velocity dispersion of the bulge is $300 v_{300}\,{\rm km\,s}^{-1}$, is $E_{\rm bulge} \approx 2 \times 10^{-6} v_{300}^2 M_{\rm bulge} c^2$. The energy from the central black hole $E_{\rm AGN} \approx 5 \times 10^{-4} M_{\rm bulge} c^2$. So only one per cent of that energy can have a major effect on the formation of that bulge. Of course, the energy needs to be in the right form. Radiation if ionizing can be damaging, but most is reradiated quickly. Relativistic jets are probably too fast to couple to the medium in the bulge well (this could explain why black holes in radio galaxies grow to be so massive). An uncollimated fast wind is perhaps the most effective agent.

5. Final thoughts

Many deep sky X-ray sources are absorbed AGN. The absorption occurs in dusty gas and is reradiated in the mid- to far-infrared bands. Chandra probably will not detect many Compton-thick AGN; XMM may do better if it can go deep in the band above 7 keV. The presence of the most massive black holes in the most massive local galactic bulges means that the most powerful absorbed AGN will be in the most massive early-type hosts at higher redshifts. The locally observed relation $M_{\rm BH} \propto v^4$ can be obtained from wind ejection, supporting evidence that powerful uncollimated winds are common in quasars. Local Seyfert galaxies may either by younger or rejuvenated black holes, which may not provide a good guide to the dominant sources of the XRB. Ultradeep X-ray images may not prove to be the best way to study the accretion history of the Universe, they may instead reveal more about the X-ray foreground, i.e. nearby galaxies. Larger numbers of sources are found by images reaching to the break in the source counts at $10^{-14}\,{\rm erg\,cm}^{-2}\,{\rm s}^{-1}$, the more distant of which may prove to be the more interesting. There is lots of power due to accretion in the Universe, most of it obscured and most only directly accessible to hard X-ray observations.

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